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TECHNOLOGY

PROJECT TINKERTOY

Modular Design of Electronics and Mechanized Production of Electronics

AN AUTOMATIC production line for the manufacture of electronic products and a novel system of electronics design that makes this possible have been developed by the National Bureau of Standards. The program, code-named PROJECT TINKERTOY, was sponsored by the Navy Bureau of Aeronautics.

Starting from raw or semiprocessed materials, machines automatically manufacture ceramic materials and adhesive carbon resistors, print conducting circuits, and mount resistors, capacitors, and other miniaturized component parts on standard, uniform steatite wafers. The wafers are stacked very much like building blocks to form a module that performs all of the functions of one or more electronic stages. Automatic inspection machines check physical and electrical characteristics of the parts-mounted wafers at numerous stations along the production line. The completed module is a standardized, interchangeable subassembly combining all of the requirements of an electronic circuit with ruggedness, reliability, and extreme compactness.

1. Description of Project

PROJECT TINKERTOY, as the program is code-named, was begun by NBS in May 1950 and now successfully produces electronic subassemblies by mechanized means. The pilot plant is operated by a commercial contractor as part of a large-scale production evaluation program under the Bureau's technical direction. The basic objective of the Navy Bureau of Aeronautics in establishing the program was the development of facilities or systems suitable for rapid mobilization in emergency periods. The facilities are also dual-purposed in nature and are expected to substantially reduce lead time in production.

MDE Design System

The key to the automatic, mechanized production of electronic equipment in PROJECT TINKERTOY is the design system developed by the National Bureau of Standards. Called MDE—for Modular Design of Electronics—the system establishes a series of mechanically standardized and uniform modules (or building blocks), producible with a wide range of electrical characteristics.

Each module, in general, consists of some 4 to 6 thin ceramic wafers, bearing various circuits associated with an electronic stage. A number of individual modules are combined to form a major subassembly. The composition of modules into major subassemblies of electronic equipment is possible because there is great similarity between circuits and parts of circuits in modern electronic equipment.

Electronic assemblies consist largely of electronic tubes and arrays of simple parts (like resistors and

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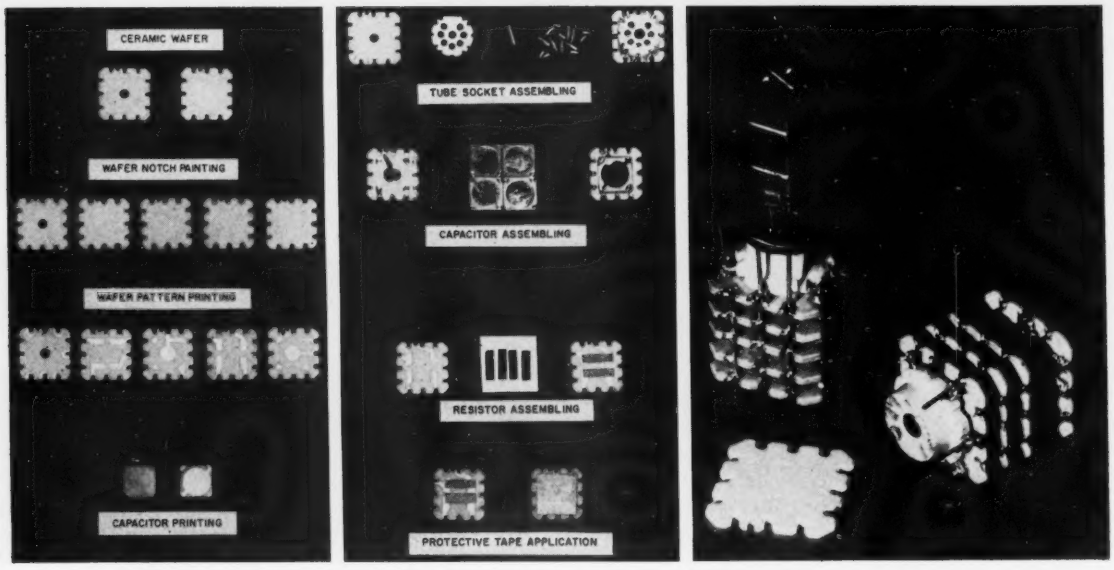
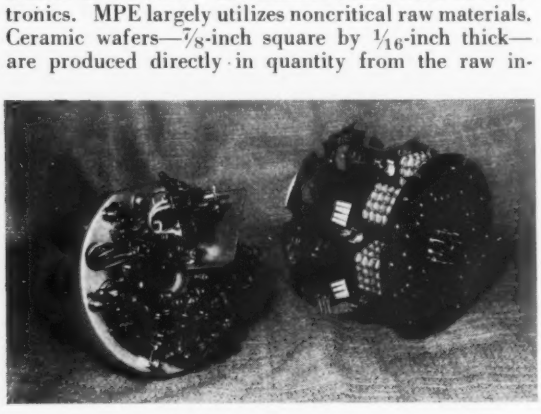


Left: **Ceramic metalizing. The MPE wafer receives a variety of circuit patterns after notch painting. The capacitor body receives a disk pattern and four corner tabs on both surfaces.** ***Center:*** **MPE parts assembling. Shown are MPE parts composing tube socket, capacitor wafer, and resistor wafer.** ***Right:*** **The module. Each module is composed of four to six wafers bearing printed conducting circuits, tape resistors, capacitors, tube sockets, and other miniaturized electronic component parts.**

capacitors) that account for the mass of the individual parts and are also responsible for the bulk of the manual production efforts in conventional production. These assemblies have been the chief target for redesign in the MDE system.

MPE Production System

The production of modules and assemblies, designed in accordance with the MDE system, is achieved mechanically in PROJECT TINKERTOY. The production system developed by the National Bureau of Standards is called MPE—Mechanized Production of Electronics. MPE largely utilizes noncritical raw materials. Ceramic wafers—$\frac{7}{8}$-inch square by $\frac{1}{16}$-inch thick—are produced directly in quantity from the raw ingredients. Ceramic capacitors are produced in a similar fashion. Another part of the line produces adhesive tape resistors.



Electronic equipment produced by conventional hand methods employing conventional parts (left) and an MPE version of the same piece of equipment.

These and other basic parts are fed into the production line. The appropriate circuits are printed by automatic machines. The circuit configuration is achieved through photographic processing. Quality control is established by automatic inspection, directed by information prepared in punched card form. Special components, not suitable for "printing" techniques, can be incorporated into the modules. Automatic physical and electrical inspection is provided for in the production line.

The MPE system is based on the use of bulk or semiprocessed materials, and the line produces all the large-quantity parts except for the tubes. The pilot plant is designed for a production goal of 1,000 modules per hour. Joining modules together to form subassemblies may also be accomplished by machines.

PROJECT TINKERTOY was sponsored by the Industrial Planning Division of the Navy Bureau of Aeronautics as an industrial preparedness measure. One of the serious bottlenecks in emergency periods has turned out to be the production of electronic equipment, upon which the military services are increasingly dependent for success in modern defense. PROJECT TINKERTOY indicates that lead time in production can be reduced 75 percent.

Currently, the PROJECT TINKERTOY line is being operated by a commercial firm under a Navy contract. The present program includes the collection of production data from which can be obtained cost figures, quality control techniques, and production refinements.

2. Modular Design of Electronics

MDE is the basis for the PROJECT TINKERTOY system. In such a system flexibility of product and the general characteristics of conventional assembly methods are compatibly combined. At the same time product standardization and uniformity—the prerequisites for economical processing by automatic machinery—are integral aspects of the system. Interconnection is relatively simple between any number of modular units. By combining modular assemblies containing different component parts (resistors, capacitors, coils, etc.) whole electronic circuits may be developed to amplify signals, generate and shape waveforms, scale count, and perform customary electronic functions.

The MDE design system dispenses with the conventional circuit diagram of the tested electronic model and places all necessary production programming information on an MDE work sheet. Each work sheet contains the front and back outlines of six wafers with appropriate numbering to identify each notch in the wafer, each riser wire, and the electronic piece that is to be placed on the wafer. The engineer translates his conventional wiring diagram to an MDE diagram. He indicates the position of the piece and its proper value and tolerances. Lines are drawn to indicate how the circuits between wafers are to be connected.

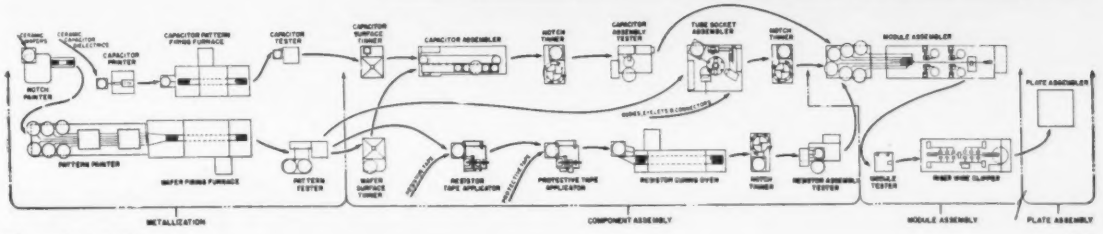
The engineer's MDE work sheet becomes the basic document from which a draftsman draws an ink drawing that may be reproduced in large numbers. The draftsman also prepares a larger version of the work sheet that is photographed and is subsequently used to make stencils for the circuit-printing machines. The numbers of wafers and the tube sockets listed on the MDE work sheets give an indication of the quantity of raw ceramic materials that must be mixed. The number and value of resistors marked on the work sheets determine the production required for tape resistors.

The MDE work sheet is also used to establish the inspection procedure. Current paths on each wafer are marked on specially prepared punch cards. These cards accompany the wafers through all of the manufacturing processes. The sheet is also used in the construction of the standard modules or counterparts that are employed in the final testing and inspection of the module assembly.

3. Mechanized Production of Electronics

MPE consists of the mechanized production of ceramic wafers, titanate capacitors and tape resistors and their automatic mechanical assembly and inspection. In some military equipment a single chassis may have as many as 100 resistors and 100 capacitors. The facil-

Right: **Interior of National Bureau of Standards MPE pilot plant. Mechanized Production of Electronics is the application of machine techniques to the manufacture of electronic equipment. For the production of MPE equipment, the present machines manufacture ceramics, process and apply piece parts to wafers, assemble modules, and automatically perform complete inspections.** ***Below:*** **Schematic diagram of the MPE pilot plant's mechanized assembly line.**



ities of the NBS PROJECT TINKERTOY plant provide for the manufacture of nearly all of these pieces from raw materials.

MPE Steatite Production

MPE wafers and tube sockets are made from talc, clay (kaolin), and barium carbonate, which in combination yield a ceramic with excellent electrical characteristics. The minerals are mixed, milled, and dried to a flour-like consistency. Binding agents of corn flour and petroleum-base wax are added, and the mixing-drying operations are repeated. Before final compounding the flour is graded according to particle size. By carefully combining particles of different sizes the ceramic product will have no laminations, be perfectly flat, and will have no air pockets within the structure.

After the addition of zinc stearate, which acts as a lubricant, the powder is pressed into either one of three wafer types or a seven- or nine-pin tube socket. The press exerts pressures up to 10,000 lb/in^2 and can stamp 2,300 wafers an hour. The "green" or uncured ceramic bodies are machine-loaded onto setter tiles, which are then conveyed through a tunnel kiln operating at a high temperature of 2,300° F. The curing operation is completed in 9 hours.

After curing, the wafers are gaged in a machine that accepts all wafers no thicker than $0.0625+0.008$ in. and 0.875 ± 0.003 in. square.

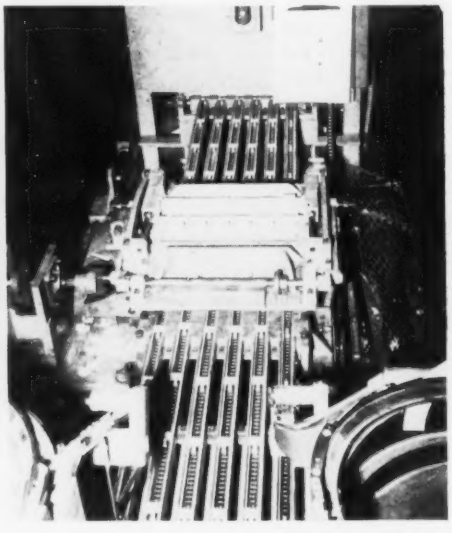
The standard wafer is pressed with 12 peripheral notches (3 on a side) and a keying notch on one side. In the final module assembly, riser wires are mechanically soldered into the 12 notches and serve as physical supports for the module and electrical connectors between wafer-mounted circuits. The keying notch is a medium by which individual wafers are automatically oriented for the mechanical application of component parts.

MPE Capacitor Production

The titanate capacitor body is manufactured in PROJECT TINKERTOY in very much the same manner as the ceramic wafers. The capacitor is nonporous ceramic composed usually of magnesium, barium, calcium, and strontium titanates of high purity, organic binders, and water. After firing, it is about ½-inch square and $\frac{2}{100}$-inch thick. Capacity may be varied from 7.0 micromicrofarads to 0.01 microfarad by changing the relative proportions of the constituent minerals. Raw material batches weighing about 5 lb will produce about 100,000 capacitors.

Although the manufacture of capacitor bodies is very similar to the production of MPE wafers, greater control must be exercised during the various operations. For instance, a rubber-lined ball mill and Pyrex drying dishes are used to eliminate the possibility of steel dust and oxides contaminating the mixture. Extreme care is exercised during the mixing and firing operations so as to maintain control over the shrinkage that normally occurs in the ceramic body. Because the capacitor is composed of highly abrasive and hard materials, only carbide steel dies appear to give satisfactory long-term service. Furthermore, capacitor bodies having high dielectric constants have a tendency to decay in capacitance value with shelf life. Adequate allowance for this decay is made in subsequent silvering operations on the production line.

Left: **Robert L. Henry, NBS project leader, and the MPE wafer pattern printer. He is indicating the special mounting in which a stencil screen bearing circuit patterns is mounted.** ***Right:*** **As the wafers are issued from the vibratory feeders, they are passed under a stencil screen bearing circuit patterns for each wafer. Up to six wafers are stenciled simultaneously with the appropriate silver conducting circuit. The paint is partially dried in the oven (background), and the wafers are also inverted.**



MPE Tape Resistor Production

The materials required for the manufacture of tape resistors in PROJECT TINKERTOY are a heat-resistant asbestos paper tape known as Quinterra, polyethylene tape, carbon black or graphite, resin, and a solvent. The resistor formulation (a mixture of the carbon, resin, and solvent) is ground to a fine adhesive powder. The compound is then sprayed on a loop of Quinterra tape, and a protective coating of polyethylene tape is applied. The tape is slit into five or six narrow strips and stored on rolls in a refrigerator. A 75-foot roll of tape will produce over 10,000 resistors. The tape resistors produced have a range from 10 ohms to 10 megohms. They will hold their rated resistance within ± 10 percent up to temperatures near 200° F. and are capable of $\frac{1}{4}$-watt power dissipation at the operating temperature.

MPE Metalizing

Metalizing is the name given to a series of operations in the PROJECT TINKERTOY plant in which appropriate sections of the wafer or capacitor body are silver-painted. During these stages, circuits are printed on the wafers, notches are coated, conducting surfaces and leads are applied to capacitors, furnace-curing takes place, and circuits are inspected. Finally, all silvered surfaces receive a thin coating of solder. All of the operations are mechanized.

The steatite wafer, the basic element in MPE, is first metalized in a machine that deposits silver paint in the 12 peripheral notches. Chain-driven grippers carry the wafers past four sets of printing wheels. Each wheel is composed of three disks that engage the notches on one side of the wafer in synchronism with the chain drive.

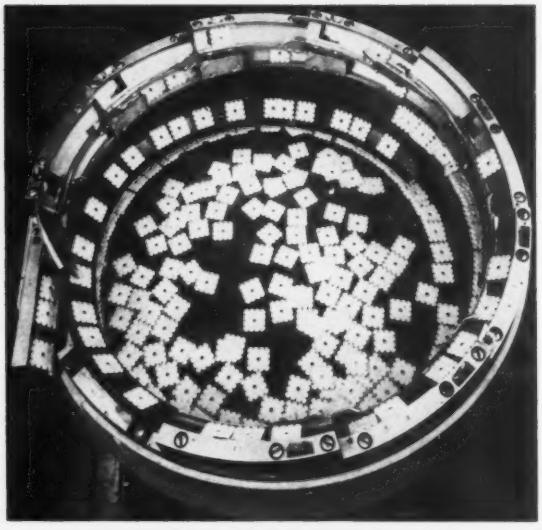
Various conducting circuits are printed on the wafers in a machine that can print up to six wafers simultaneously. The patterns (as many as six) are photoetched on a rectangular stencil screen and usually include the lead connections to which will be attached the tape resistors, tube pins, and other electronic parts. The wafers are conveyed under the stencil where chain-driven squeegees force silver paint through the patterns onto the wafers. The wafers then pass through a heater in which they are inverted and the unprinted surfaces are exposed to a second stenciling operation. After another heating-drying period, the wafers are conveyed through a firing furnace in which the silver paint is made highly conductive and physically and chemically bonded to the ceramic surfaces.

The conducting pattern for the MPE capacitors is a solid square of silver covering most of the surface area and small tabs of silver at the four rounded corners of the body. The pattern is repeated on both surfaces of the capacitor except that one receives an additional bar of silver connecting two diagonally opposite corner tabs with the central square. Two circular stencil screens, with photoetched patterns, simultaneously print both surfaces of the capacitor body.

MPE Materials Handling

The keying notch pressed into each wafer is initially used during the metalizing operations. The wafers are loaded into vibratory bowl feeders provided with spiral escape channels. A series of eight exit ports followed by steps are set into the channels. A small screw is inserted into each exit port that permits only those wafers

Left: **Surface tinning. Silver-painted surfaces in capacitor body are tinned in a machine that automatically dips the body into flux, solder, and then a wash.** ***Right:*** **Pattern inspection. Conducting circuits are inspected automatically. Punched cards set up appropriate test circuits in the electronic inspector.**



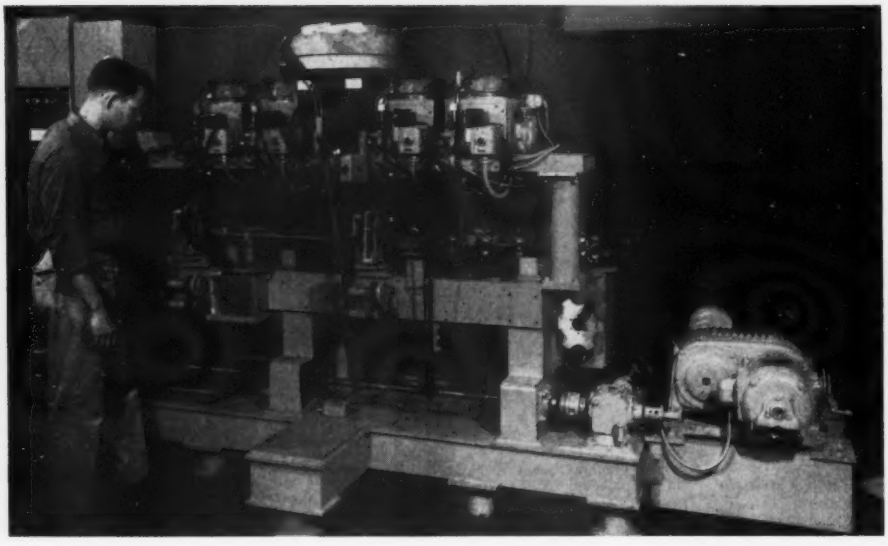
to pass whose key is alined with the screw. If the wafer is incorrectly oriented, it is turned 90 degrees as it falls down the channel step following the exit port. A specially grooved channel inverts the wafer if it has failed to pass through the first four ports, and the keying procedure is repeated. As a consequence, all wafers passing from the feeders are oriented in the same direction and have the same surface turned upward.

Another feature of the vibratory bowl feeders is the mechanism that controls the quantity of wafers being issued. The issuing channel is provided with a photoelectric cell that functions only if the light path is completed. If the channel is not filled with wafers, the completed photocell light path energizes the circuit causing the bowl to vibrate. When the channel is full, the bowl automatically stops vibrating and, therefore, issuing wafers.

MPE Components Assembly

Tape resistors, titanate capacitors, tube sockets, and other miniaturized parts are mounted on the wafers between the appropriate silvered conducting patterns. Rolls of resistor tape are placed on a machine that automatically cuts the tape into one-half inch lengths, presses the resistors between the printed electrodes on the surface of the wafer, applies pressure, and ejects the completed resistor-mounted wafer. As many as two resistor tapes may be applied to each wafer surface.

A single machine is used to mount up to two capacitors on each surface of a wafer. Each capacitor is automatically oriented and the silvered circuit on both surfaces is electrically tested before mounting. For example, if four capacitors are to be mounted on a wafer, the first two are dropped into a conveyor-driven jig. They are followed by a slave that centers the capacitors, and the properly oriented wafer is added. The remaining two capacitors are dropped on top of the wafer. The jig is conveyed through a pair of in-



Top: **Vibratory bowl feeder. Each MPE wafer has twelve peripheral notches and a keying notch. Key serves to orient the wafer during machine operations. Exits in spiral channels, provided with keys, permit only properly oriented wafers to be issued.** ***Center:*** **Tape resistor application. One or two ½-inch strips of resistor tape may be applied to each surface of a wafer.** ***Bottom:*** **Capacitor assembly. One or two capacitors may be bonded to each wafer surface. The machine automatically orients, assembles, and bonds the capacitors to the wafers.**

duction heaters that cause the tinned surfaces on the parts to bond.

In the tube socket assembler, silvered tube pins are mechanically placed into their proper holes in the steatite tube socket, a wafer is placed on top of the socket, and a rivet binds the two pieces together.

After the various parts have been mounted on the wafers, the notches on the wafer are tinned with solder. The machine that performs this operation automatically grips each component-mounted wafer and dips one side into flux and solder. The tinning operation is repeated on the other three sides after successive 90-degree turns of the wafer.

MPE Module Assembly

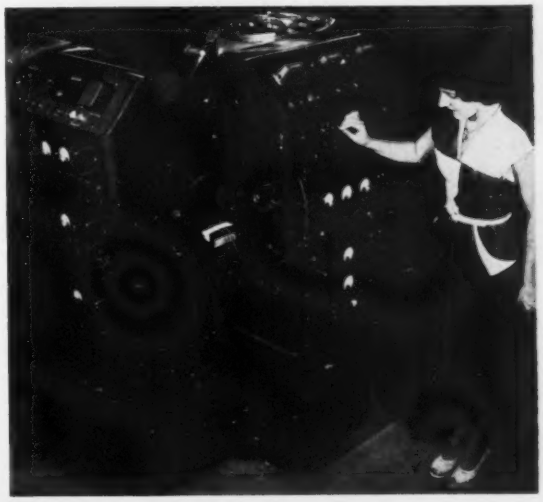
Uniform wafer-mounted component parts, including wafer-mounted coils, toroids, potentiometers, and crystals are now ready for assembly. The complete assembly of the module is accomplished in a single machine. Six vibratory feeders issue the wafers to a loading device that holds the wafers in an upright position between specially designed jaws. A chain drive carries the jig to a soldering position at which six riser wires are guided into appropriate notches, three on a side. The mechanism brings soldering irons in contact with the unit and bonds the wires to the notches. The unit is turned 90 degrees, and the chain drive carries it to another soldering position where six more wires are bonded to the module. After final electrical inspection, segments of riser wires are severed where circuit isolation is required between wafer-mounted circuits.

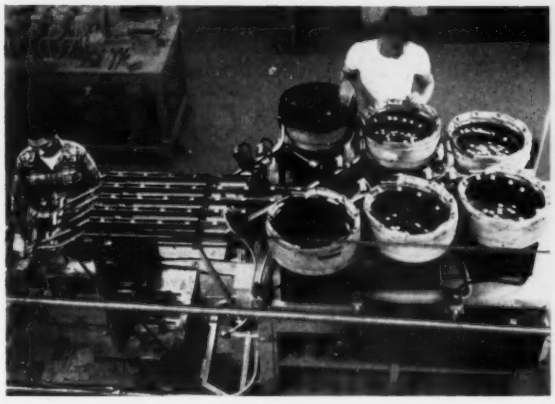
Right: **Capacitor-wafer inspection. Capacitor-mounted wafers are automatically checked for capacitance, leakage resistance, and break-down voltage.** ***Below, left:*** **Module assembler. MPE parts-mounted wafers are loaded in vibratory bowl feeders that issue single, oriented wafers into a stacking jig (left). Up to six wafers may be stacked to form a module.** ***Below, right:*** **Soldering operation. Three pairs of wires are guided into three notches on opposite sides of the stacked wafers. Soldering irons, shaped to engage only the wafer notches, automatically bond the riser wires to the module.**

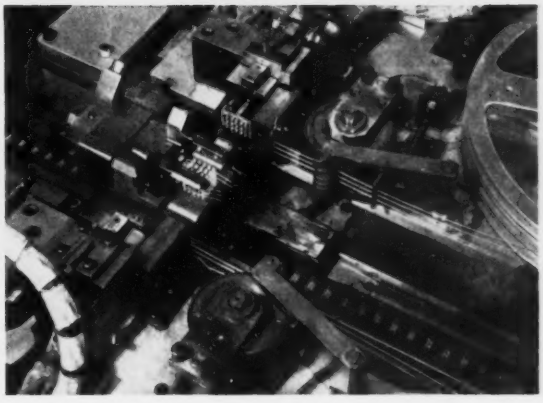
MPE Automatic Inspection

During each stage in the Mechanized Production of Electronics, provision is made for 100-percent automatic inspection. This is both a physical gaging and an electrical comparison. Printed circuits, resistors, and capacitors are compared with their electronic equivalents both before and after assembly. This is accomplished by use of electronic computers, bridge circuits, and other comparison devices. The inspection "code" is contained on the punched cards that were prepared by the design engineer and have accompanied the wafers all through the production process. After the final assembly of the module the whole circuit is again tested to see that it meets specifications within set tolerances.

The circuit-mounted wafers are automatically inspected in a machine that determines if the patterns have been correctly stenciled, and if all of the wafers in a particular batch are alike. The punched holes in the inspection card electronically set up computer circuits. Thus, if two notches are to be connected by a painted conductor, the corresponding circuit in the com-







puter is disconnected. If the printed pattern appears between the two points in question, the computer recognizes it as a completed circuit and signals a relay to accept the wafer. Up to 72 combinations may be printed between 22 possible connecting points on the surfaces of an MPE wafer.

The capacity inspector incorporates two commercial precision capacitors with a range of from 110 to 1,100 micromicrofarads and a precise comparison bridge. One precision capacitor is set at the upper tolerance limit of the required capacity; the other capacitor is set at the lower tolerance. As the titanate bodies exit from a vibratory feeder, the silver surfaces are first checked for continuity. Then they are admitted to the circuit containing the precision capacitors and bridge. Only those bodies with their capacity between the set tolerances are accepted. The automatic inspection of a single capacitor can be accomplished in less than half a second.

After the capacitors have been bonded to wafers, the unit is automatically inspected for capacity, voltage breakdown, and leakage resistance. The capacitor-mounted wafers are issued from a vibratory feeder onto a turntable. Twelve fingers engage the peripheral notches on the wafer and provide conducting paths between the capacitors on the wafer and a "standard" network composed of precise conventional-type capacitors. If accepted, the turntable moves the wafer under another inspecting head where again the notches are engaged and voltages are applied along appropriate conducting paths. The magnitude of the breakdown voltage is determined by the actual operating conditions the unit will undergo. The leakage resistance must be at least 8,300 megohms between conducting circuits.

The resistor-mounted wafers are inspected in a machine very similar in operation to the capacitor-wafer inspector. Prior to application to the wafer, the rolls of tape had been tested for correct resistance. The resistor-wafer is automatically compared with a conventional resistor network in a bridge circuit.

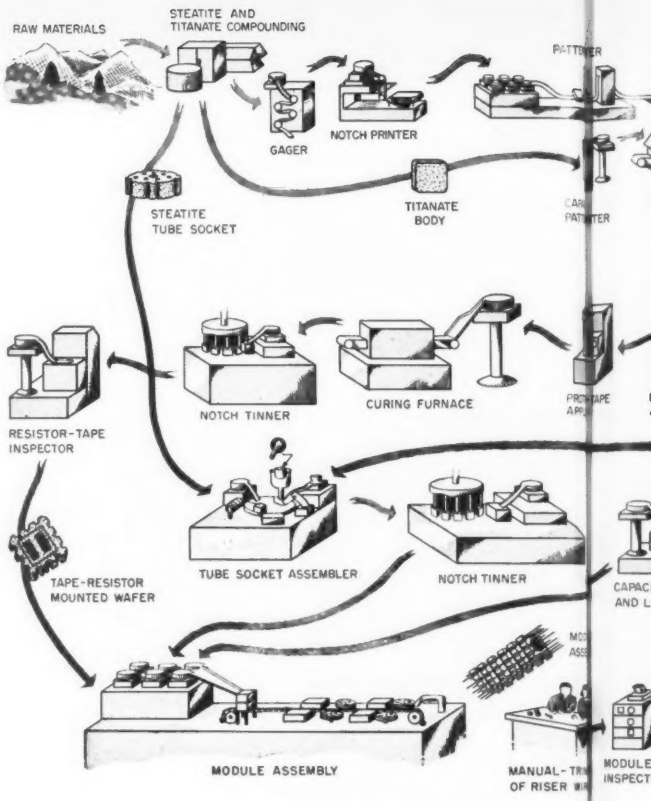
The completed module is inspected in a machine that sequentially compares it with a "standard" module composed of conventional resistors, capacitors, coils, etc., arranged in accordance with the original MDE engineered circuit.

Final Assembly

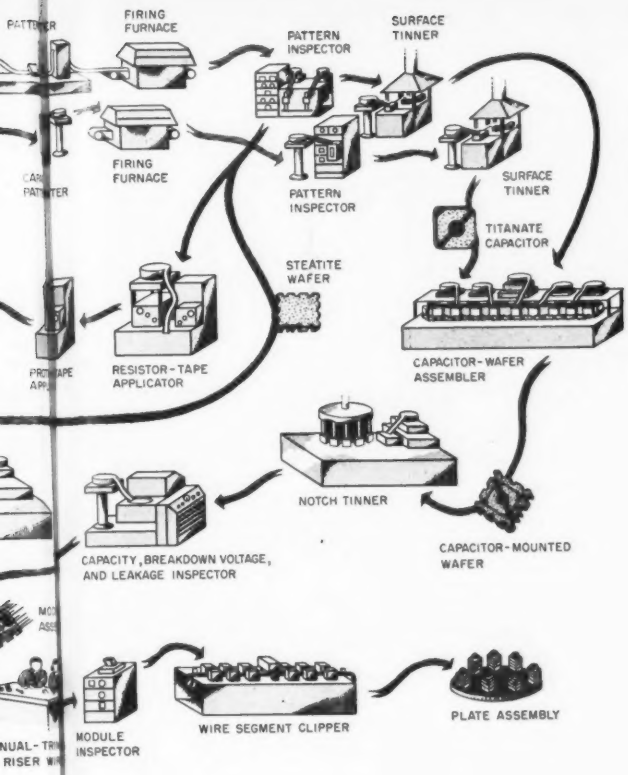
The final assembly operation need not necessarily be considered a part of the Mechanized Production of Electronics. Normally, a set of modules (as many as ten) are mounted on or between copper-clad base plates. Circuits have been etched into the copper surface and connect the riser wires of the several modules to form a complete electronic circuit. Several such plate assemblies may form an equipment. One base plate with six modules, for instance, contains all the necessary circuits to make a six-tube radio receiver function properly.

4. Industrial Preparedness

Industrial mobilization and preparedness have been studied by the Industrial Planning Division of the Navy



Above: **Flow diagram of MPE pilot plant.** *Below left:* **Mr. Hood MPE been assembled into a module, excess portions of riser wires removed a module complete with vacuum tube.** *Below right:* **Segment of Circuit of specified riser wires at top and bottom of module. Com circuits n**



Mr. Head MPE module inspector. After parts-mounted wafers have wires severed and the unit is inspected. Mr. Henry is holding MPE ment ci Circuit connections to module are determined by the clipping . Comcuits may be achieved by severing riser wires between wafers.

Bureau of Aeronautics for many years. In studying the electronic industry it was concluded that in the event of a national emergency costs for production and maintenance of electronics would be formidable in view of the quantities and varieties of needed gear. Consequently the Navy Bureau of Aeronautics decided that the only solution to the problems of satisfying the huge demands for electronic equipment was a mechanized production system.

The Navy turned to the National Bureau of Standards in 1950 for the solution of these industrial mobilization problems. The National Bureau of Standards had engaged in pioneering work in printed electronic circuits, stemming from problems arising in its proximity fuze work during World War II. Prior to 1950, the Bureau had developed a modular design concept, tape resistors, special circuit-printing techniques, and hand-machines for printed circuits in connection with various research and development projects. Problems of miniaturization and ruggedization of electronic equipment had also been under study for some time.

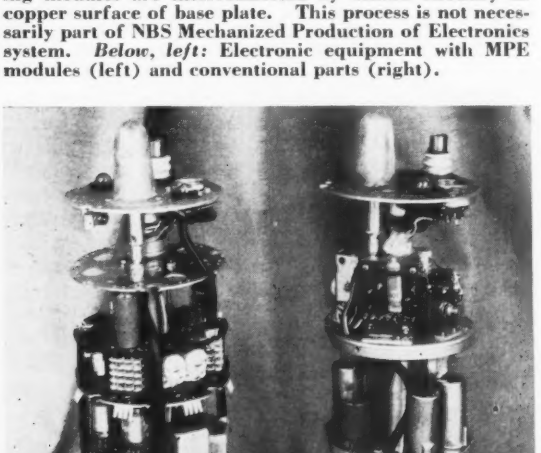
The first modular design of military electronic equipment had been completed by NBS in 1949, when a radar intermediate frequency assembly had been designed and constructed. A careful study by the Navy in 1950 indicated that "the most advanced state of processed circuitry is available at the National Bureau of Standards." The NBS system was particularly compatible with military environmental requirements, and stressed maximum use of raw materials rather than preprocessed component parts. The major objective of the program became the design and construction of a pilot plant compatible with the principles of Modular Design of Electronics.

PROJECT TINKERTOY makes possible a rapid conversion from civilian to military products (and back again) on short notice and, concurrently, allows a greatly expanded production capacity. Delays caused by the need for recruiting and training new production personnel and the procurement of new mechanisms and parts are eliminated. Most of the operating "know-how" is stored in mechanical fingers and electromechanical control mechanisms, and even electronic equipment designs may be stored, ready for production, in the form of punched cards and circuit stencil screens.

Because PROJECT TINKERTOY largely utilizes unprocessed or bulk materials, the system is comparatively free from dependence on particular components in critical supply. The Mechanized Production of Electronics results in a very high production rate. Uniformity of electronic products at a high quality level is enhanced by the mechanized production and by 100 percent automatic inspection. This affords the possibility of repair and maintenance of electronic systems by replacement of unitized packages or entire subassemblies.

Performance of equipments produced in PROJECT TINKERTOY appears generally equivalent to that obtainable from conventional assemblies. Equipments produced on an experimental basis meet military environmental requirements, passing such tests as shock,

Above: **Base plate assembly. Completed modules, performing specific and complete circuit functions, are manually mounted on base plates to form entire electronic subassembly. Wafer-mounted component parts composing modules are interconnected by etched circuitry in copper surface of base plate. This process is not necessarily part of NBS Mechanized Production of Electronics system.** *Below, left:* **Electronic equipment with MPE modules (left) and conventional parts (right).**



vibration, temperature, and humidity established in military specifications. Moreover, the standardization and uniformity achieved by the MDE wafer-component and stacked-wafer design result in production outputs of uniformally satisfactory equipment, whose characteristics both physically and electrically are controlled through the 100-percent automatic inspection machines that are an integral part of the production line.

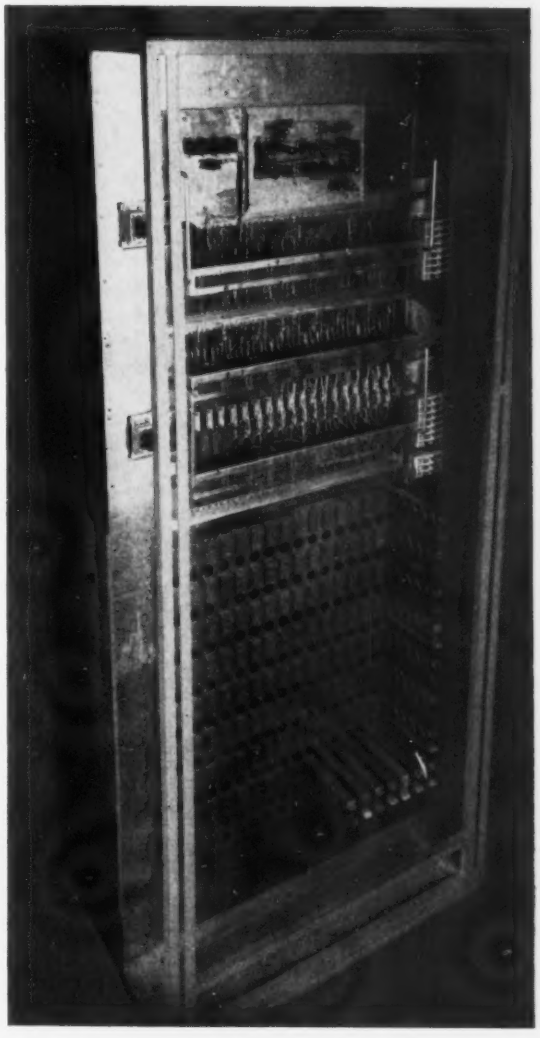
The final design and subsequent construction of many PROJECT TINKERTOY machines called for the services and assistance of industry at a time when the Korean emergency had preempted most machine-tool and related facilities. The Navy and the National Bureau of Standards were able, however, to secure the cooperation of several companies with available facilities and staff.

Basic conception and development—as well as early background research—were contributed by the National Bureau of Standards, including solution of new process and materials handling problems, design of the pilot plant and much of its equipment, and technical direction of all phases of the program. While some of the plant machines were designed and constructed by NBS, the major part of the design and construction of the production equipment was done by the Kaiser Electronics Division of Willys Motor Co. (The PROJECT TINKERTOY line is currently being operated by the Kaiser Electronics Division under a Navy contract for the production of naval electronic equipment.) Some special machines were also designed and built by the Doughnut Corp. of America (Ellicott City, Md.). Specially designed automatic production test equipment was obtained principally from Communication Measurements Laboratory, Inc. (Plainfield, N. J.). Some major engineering applications to equipment were made by Sanders Associates, Inc. (Nashua, N. H.), including environmental studies of MDE units. The Davies Laboratories (Riverdale, Md.) and the Navy Post Graduate School (Monterey, Calif.) also rendered assistance in some phases of the work. Acknowledgment is also due to many companies and individuals who contributed auxiliary services and supplies.

For further technical details, see Printed Circuit Techniques, *NBS Circular 468 (1947), on sale by the Government Printing Office ($0.25);* New Advances in Printed Circuits, *NBS Miscellaneous Publication 192 (1948), on sale by the Government Printing Office ($.45);* Electronic Miniaturization *(NAer 00685, National Bureau of Standards Final Report), OTS Report No. PB–100949 (1949), 189 p., $4.75;* Printed Circuits *(NAer 00686, National Bureau of Standards Final Report), OTS Report No. PB–100950 (1950), 99 p., $1.75;* A Subminiature Low-Frequency Radio Receiver, *NBS Technical News Bulletin* **35,** *68 (May 1951), 10 cents;* Miniature Intermediate-Frequency Amplifier, *NBS Technical News Bulletin* **35,** *143 (Oct. 1951), 10 cents;* Circuit Printers for Flat and Cylindrical Surfaces, *NBS Technical News Bulletin* **35,** *168 (Nov. 1951), 10 cents;* Development of the National Bureau of Standards Casting Resin, *NBS Circular 493 (1950), 10 p., 10 cents;* Printed Circuit Techniques: An Adhesive Tape Resistor System, *NBS Circular 530 (1952), 83 p., 30 cents;* NBS Precured Tape Resistor, *NBS Technical News Bulletin* **36,** *110 (July 1952), 10 cents; and* New Methods of Radio Production *by J. A. Sargrove, J. Brit. Inst. Engrs.* **8,** *No. 1, 1 (Jan.–Feb. 1947).*

A DIODE-CAPACITOR MEMORY

for high-speed electronic computers



Experimental unit housing the new diode-capacitor memory developed in the NBS electronic computers laboratory. The top half contains chassis using standard NBS packaged computer circuits, and the lower half holds the special packages utilized in the memory itself. Use of packaged circuitry facilitates trouble shooting, and faulty components may be replaced quickly.

CONTINUED research on rapid-access memories for high-speed electronic computers has resulted in the development of an information-storage device utilizing diodes and capacitors as the basic storage units. Developed by A. W. Holt of the Bureau's electronic computers laboratory, a recently completed prototype memory based on this idea appears to be faster than any other system. It more than matches the speed of the arithmetic unit used presently in SEAC (National Bureau of Standards Eastern Automatic Computer) and should at the same time, because of its simplicity, be more reliable than other memories now in use. The most difficult part of the basic problem of high-speed access was overcome by the development of a selector matrix switch using diodes and transformers. The test system was recently connected to SEAC, and a continuous checking program was run on it for 12 hours without a single error.

Modern electronic computers have been handicapped by the inability of the memory to attain speeds matching practical arithmetic units. Acoustic memories are slow because they depend on serial presentation of information to the computer. The Williams cathode-ray tube storage system is a distinct improvement because information can be supplied in parallel, but access time is still not small enough to balance the capabilities of possible arithmetic units. The diode-capacitor memory, however, which can be designed to present in excess of 100,000 randomly located 50-digit words per second to the computor, attains a speed corresponding to that of the arithmetic unit, with a resulting decrease in machine computation time for mathematical problems. In contrast, SEAC's acoustic memory has a random access of 6,000 words per second while the Williams memory has an access rate of up to 60,000 words per second.

The system developed by NBS uses ordinary linear capacitors as discrete storage elements in a matrix arrangement. These capacitors provide memory by storing one of two voltage states. The charge that gradually leaks away through the associated circuitry is periodically restored. The memory circuit employs two diodes and a capacitor for each digit stored. This type of memory promises very high reliability if properly constructed because the minimum signal is of the order of 1 or 2 v and need only be recognized as positive or negative in order to read the information. In the mercury memory and Williams memory schemes the value of the low-level signal output is critical.

The basic circuit for the storage element consists of two diodes in series, with the anode of one connected to the cathode of the other, one side of a capacitor tied to their midpoint, and the other side of the capacitor returned to ground through a resistor. The point between the capacitor and resistor, which may be denoted by "E", is used for both reading and writing, while the two diodes are used as a "squeezer" to connect the capacitor to the read-write circuits. During holding, both diodes are biased in their back direction. For example, the anode of one diode might be held at -4 v, while the cathode of the other is held at $+4$ v. Then, if the capacitor has a charge of, say, 2 v, both diodes will be biased in their back direction, and only small currents will flow into or out of the capacitor.

When the ends of the diodes are both forced to ground potential ("squeezed"), one diode or the other will conduct, and a voltage will appear across the resistor. If the capacitor has been charged with 2 v of such polarity as to make its lower terminal more negative than its upper terminal, there will appear at the output E a pulse of -2 v, which dies out with the time constant RC. This negative pulse is recognized by the reading circuits at the output as the binary digit "zero". If the polarity on the capacitor had been in the opposite direction, the squeeze would have produced a positive pulse that would be recognized as the binary digit "one". Thus, the content of the storage element has been read; but in the process it has been at least partially discharged, and the information has been lost from the storage element. The information must be rewritten to continue the storage beyond the reading operation.

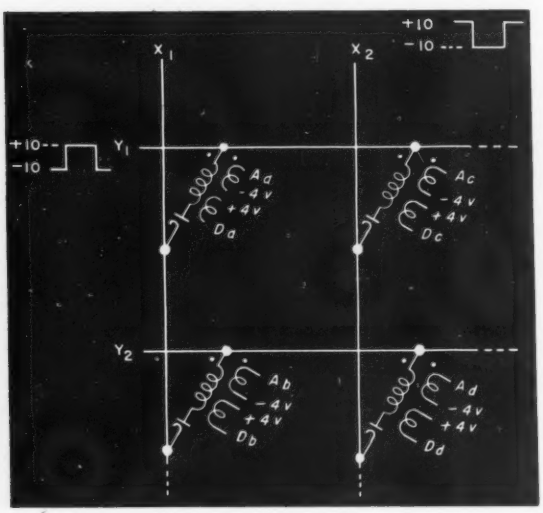
In order to write (or rewrite) information it is only necessary to force the point E to the desired state and hold it there until the squeeze is over. While the ends of the diodes are at zero voltage, assume that E is forced to $+2$ v and held there until the diodes are returned to their normal voltages of -4 and $+4$ v. Then the capacitor is left with a charge of 2 v and upon the next squeeze will produce a positive pulse at E, i. e., a "one" has been written. The opposite is equally possible: forcing E negative until the end of the squeeze will write a "zero". Once the diodes have been returned to their normal voltages, the charge on the capacitor will be undisturbed by later changes at E, provided that the magnitude of the voltage at E never exceeds 2 v. Thus E can have other pulses on it, either positive or negative, and the charge stored on the capacitor will remain unaffected because both diodes will remain with backward bias. This is important for organizing many basic storage elements into an efficient memory assembly and is the reason for charging the capacitor to only ± 2 v while biasing the diodes twice as much.

In this description the diodes have been assumed to be ideal, having practically infinite forward conductance and practically zero backward conductance. The effect of finite forward conductance will reduce somewhat the output pulse amplitude, and it will determine how long a writing pulse must last to charge the capacitor adequately. The effect of finite backward resistance, however, is critical. During the holding operation relatively long times will elapse, and even minute currents through the diodes would disturb the capacitor charge. The unit would gradually leak toward a condition of no charge on the capacitor or even a condition on which the sign of the charge on the capacitor is reversed. Thus the permissible duration of the holding operation is determined by the rate at which the capacitor leaks charge through the diodes' back currents. Arbitrarily long periods of storage of information are achieved by regeneration; before the capacitor charge can change to a point where there is danger of losing the information, the memory control circuits read the content of each cell and rewrite it.

An amplifier is accordingly needed at point E to sense the polarity of E during the early part of the squeeze period, together with a gate structure which will force E to the desired polarity during the latter part of the squeeze period. For reading or regeneration, E is forced to the same polarity that was read; for writing new information the polarity to which E is forced is independent of what was read, but is determined by the new information being written. Such a gating amplifier is easy to construct. The amplification required is small since the input is a pulse whose amplitude is of the order of 1 or 2 v. The gating can be accomplished with standard techniques, and the circuit can be constructed using 2 or 3 vacuum tubes and about a dozen diodes.

In order to achieve acceptable efficiency, it is essential that the gating amplifier serve many basic storage elements. The busses to the diodes are made common to all the digits of a particular computer word, and a particular gating amplifier serves the same digit on each of many words. Thus for 256 words of 50 binary

A portion of the word selection matrix, using "transformer and-gates," developed at the NBS laboratories for very rapid access to information stored in the memory.



digits each there would be 256 pairs of leads to the diodes and 50 gating amplifiers. For reference to a particular word, the proper pair of busses are squeezed to zero voltage, while all the other pairs are held at their normal value of -4 and $+4$ v. In this way each gating amplifier receives a pulse from its particular digit of the selected word so that the word is available in parallel at the gating amplifiers. They can then write into this word or rewrite it without affecting the other words in the memory since all diodes in other words remain with backward bias. After the squeezing busses on this word are returned to normal, any other word may be referred to in the same way. This is the basis of a fully parallel, random-access memory. Regeneration is handled by having the memory control intersperse regeneration cycles, in which the words are read one after the other and rewritten into their former state, between the computer access cycles.

The system described achieves reasonable efficiency for the gating amplifiers but requires a selection circuit capable of squeezing the appropriate pair of busses for a particular word. This could be accomplished by the customary diode matrix, but the usual form of such a matrix requires large standby currents. In this memory the squeezing busses call for relatively high currents; the resultant diode selection matrix is feasible but not practical because it draws a large amount of standby power. To avoid this, a selection matrix consisting of transformers and diodes is used which has no standby power requirement, although it does require more input drivers than would be necessary with a multidimensional diode matrix. For the "transformer and-gate" matrix, developed at the NBS electronic computers laboratory, $2n$ inputs are required to select from n^2 words. The matrix is made up of two sets of crossing busses, X and Y; at each crossing a diode and transformer primary are connected in series, with the cathode of the diode tied to the X bus. Normally all of the X busses are held at $+10$ and all the Y busses at -10 v. This puts backward bias on the diodes associated with each transformer, so that normally no current flows through any transformer. If one X bus is dropped to -10 v, still no current flows; but if simultaneously one Y bus is raised to $+10$ v, then just one transformer at the crossing of these two busses will receive a signal, the transformer secondaries connected to the diode-capacitor will squeeze the busses together, and the desired word will be selected.

From the standpoint of ruggedness, the diode-capacitor memory is superior to the acoustic and cathode-ray tube memories. The components are light and nonmicrophonic, and no complicated mechanical problems exist. Printed circuit techniques may be used for the repetitious array, reducing assembly costs.

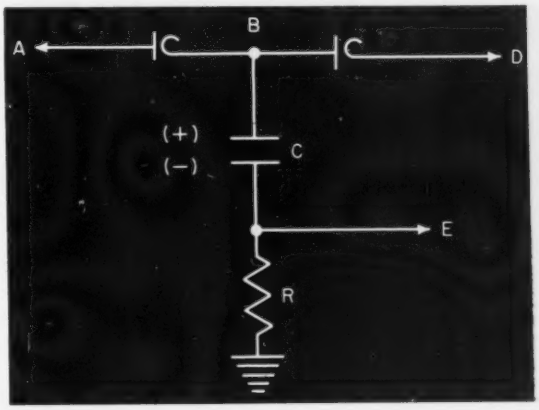
The complete repetition of the extremely simple basic circuit allows a new type of preventive maintenance. If the majority of failures have a single simple cause (low back resistance of a memory diode), a technique can be devised that will rapidly and thoroughly check for marginal diodes by means of a machine program. This routine loads the memory with a known pattern and then slows down the regeneration rate of the memory while checking for errors. Any cell that fails too soon will have its position typed out, and the cell can be replaced in a matter of seconds. The entire program could be run every hour, if necessary, without seriously detracting from computation time. Other types of marginal checks, such as voltage variation, are possible, but the regeneration check seems to be most direct.

At NBS, the elements of the diode-capacitor system were tested individually. Then a laboratory model was built containing 16 words of 4 digits each. Several storage tests were successfully carried out with this model in its final form. On 5 occasions the unit was left running for 3-day periods and on another occasion for 1 week. It was found to have the correct information at the end of each period.

Results with the laboratory model have been sufficiently promising to justify the construction of a system more nearly approaching a full memory. Thus a prototype has now been built to be tested by SEAC. The unit is designed for a capacity of 256 words of 45 digits each, but a system capable of storing only 128 words of 8 digits has been built as a start. Because the words have only 8 of the customary 45 digits, it is not now possible to operate SEAC exclusively from this trial memory unit. However, since SEAC can operate from both the acoustic and diode-capacitor memories in integrated fashion, it is feasible to do extensive testing of the new memory by using test routines stored in the acoustic memory. With 40 words connected, a test run was carried out for 12 hr without a single memory malfunction. In a test recently performed with 500 memory cells, 1 model of the diode-capacitor memory completed 269 hours of operation without a single error.

For further technical details, see An experimental rapid-access memory using diodes and capacitors, *by A. W. Holt, Proceedings of the Association for Computing Machinery, Toronto meeting, September 1953. The diode-capacitor memory was also described by A. W. Holt at the National IRE convention in March 1952.*

Circuit diagram of the basic storage element in the diode-capacitor memory supplementing SEAC's memory.



SEMICONDUCTING INTERMETALLIC COMPOUNDS

INVESTIGATIONS of the properties of semiconductors have revealed that certain intermetallic compounds show promise of extended use in solid state electronic devices. Current research, under the direction of R. G. Breckenridge of the NBS solid state physics laboratory, is concerned principally with the conductivity and the Hall effect of such metal compounds as indium antimony (InSb) and aluminum antimony (AlSb). These combinations may have equal or greater utility than the germanium and silicon semiconductors presently in large demand.

The development of silicon and germanium diodes and the subsequent discovery of the germanium triode marked the beginnings of the expansion of solid state electronics. The products of this growth in semiconductor technology have supplemented vacuum tubes in many applications and even replaced the tubes in some equipment. However, the realization of the full industrial potential of transistors and semiconducting rectifiers has been handicapped by material limitations and difficulties in the preparation of the single crystals of germanium and silicon needed for newer semiconductor devices. NBS research has been directed toward an investigation of intermetallic compounds that exhibit the same or better semiconductor characteristics and that are more easily prepared than the metals currently in use.

Early NBS research on semiconducting materials involved the preparation of "grey tin," a form of tin stable below 13.2° C. It was reasoned that this material should be a semiconductor because its diamond structure resembles that of silicon and germanium. Efforts were made to condense tin vapor on a substrate material having a crystal lattice that properly matched grey tin, which would thus assist in the growth of the low-temperature form. The substrate chosen was indium antimony, a compound which has a crystal structure unlike either indium or antimony but matches grey tin almost exactly. Although the investigation did not result in the production of grey tin, the physical properties of the InSb suggested that it might also have useful semiconducting characteristics. Later investigations on high-purity samples confirmed the hypothesis that indium antimony was actually a semiconductor and, in addition, it was found to have very high carrier mobilities (speed with which the carrier of electron current moves in electric fields). The first public announcement of these results was made at the meeting of the Solid State Advisory panel composed of representatives from leading research laboratories, November 21, 1952.

Holding device used for study of Hall effect and conductivity. Semiconducting intermetallic compounds are soldered between terminal lugs (extreme right). Measurements are made at terminals external to holder (left).

The current NBS program has involved an investigation of the Hall effect and the conductivity of several such semiconducting materials and of such related phenomena as optical absorption spectra, photoconductivity, and rectification effects. All of the studies thus far have been performed with polycrystalline samples; when methods of growing single crystals, presently being tried by NBS, have been successful, each experiment will be repeated on these crystals.

Investigations of the Hall effect and conductivity give an indication of the number of charge carriers present and the charge carrier mobility. The Hall effect occurs when a magnetic field is applied perpendicular to an electric current flowing in a conducting material. A voltage is produced within the conductor whose vector direction is mutually perpendicular to the current and magnetic field. The magnitude of the voltage depends upon the number of charge carriers in the conductor; its sign is determined by the type of conduction—either by "holes" or by free electrons.

Most semiconductors depend for their conductivity on impurities within the crystal lattice. For one type of impurity, the foreign atoms are ionized thermally and thus provide conduction electrons. Impurities of this sort are called "donors" and the material is an "n-type" semiconductor, i. e., the sign of the charge carriers is negative. In another type the foreign atom is ionized by accepting an electron ejected from the normal energy level of the material, thus leaving a hole in that level. This vacant electron site will also move in an electric field and behaves like an electron with an effective positive charge. Conduction is then by "holes" and the name "p-type" indicates the positive sign of the charge carriers. Impurities of this sort are known as "acceptors." The temperature region in which the foreign atoms act as the source of electrical conduction is called the "impurity" range. At sufficiently elevated temperatures electrons may be thermally excited in the pure material itself. This temperature region is called the "intrinsic" range.

High charge carrier mobility is a fundamental property for transistor action. In a point contact transistor

the emitter injects "holes" into the semiconductor. These holes migrate under the influence of the applied electric field to the collector where their presence influences the flow of electrons from the collector to the base electrode. The ability of the transistor to follow high frequencies depends on how fast the holes can travel from the emitter to collector; the shorter the time required, the higher the frequency. In a typical sample of high grade germanium, the mobility is about 3,000 cm^2/v sec. For ordinary-size electrodes and spacings this restricts the highest frequency to about 10 or 20 Mc. By making the contact points very small and by putting them very close together, the upper-frequency limit has been raised to about 100 Mc, but with a sacrifice of power handling ability.

Another fundamental property governing the migration of the injected holes is the purity of the semiconductors. In a highly impure sample the injected charge carrier will become trapped at a foreign atom and disappear before it has had time to migrate to the vicinity of the collector. Thus, the charge carrier will not contribute to transistor action. The number of charge carriers found in the Hall effect and conductivity measurements is a direct indication of the number of such trapping centers. At room temperatures, carrier mobility is primarily a function of the nature of the crystal lattice, with a small decrease in mobility from impurity scattering of the electron. The number of charge carriers is primarily a function of the sample purity. Consequently, if a material is found to have a high lattice mobility, its properties can be improved by purification, but a material with a low lattice mobility cannot be markedly improved.

The samples of indium antimony investigated by the National Bureau of Standards have not been sufficiently pure to give transistor action, but their mobility (20,000 cm^2/v sec) is about seven times that of germanium. With sufficiently pure samples, transistor action should be possible at much higher frequencies and at higher power levels. The mobilities in the other compounds studied (GaSb, AlSb, CdSb), while high, are apparently not as high as in InSb and may not function as well at high frequencies.

Another parameter, important with respect to the performance of practical diode and triode semiconductors, is the change in properties with temperature. In a semiconductor the number of charge carriers increases exponentially with temperature. In the impurity range this change is slow because the activation energy ΔE appearing in the exponential relationship for semiconductor conductivity, $\sigma = \sigma_0 e^{-\Delta E/2kT}$, is small. At higher temperatures the intrinsic range is reached. Here changes with temperature are much more rapid because the energy is larger. For a material to be useful, the intrinsic range should not be reached at temperatures normally encountered, i. e., below 200° C. The activation energy of germanium is 0.75 ev; its intrinsic range thus starts at about 60° C for samples of normal purity. Silicon samples of the usual purity, with an activation energy of about 1.1 ev, do not enter the intrinsic range until a temperature of approximately 350° C is attained.

Small sample is mounted on holder and placed in evacuated chamber. Magnetic field (center) is applied perpendicular to electric current flowing in conducting material. Conduction is measured with apparatus as shown but with magnetic field removed. Liquid nitrogen is shown being admitted to system for low temperature measurements.

From investigations of the temperature variation of Hall effect and conductivity, it was found that the activation energy of indium antimony is about 0.40 ev. This value is too low to allow transistor action at elevated temperatures. Gallium antimony has an activation energy of about 0.86 ev, somewhat greater than germanium, and aluminum antimony appears to have an activation energy greater than 1 ev, slightly larger than silicon. The variety of intermetallic compounds available suggests that it will be possible to find suitable combinations with proper energy to yield the desired semiconductor characteristics.

NBS research on single crystals is aimed at the preparation of junction-type diodes and triodes, particularly the *p-n* junction diode. The performance of these devices, especially in regard to their power handling ability, is markedly superior to point contact units. In addition, the theory and practice, especially for diodes, are well understood. It is to be hoped that the improved ease of handling GaSb over Si will permit the preparation of a good high-temperature diode and eventually n-p-n transistors, although this last stage may be difficult.

From a purely practical standpoint, the most important feature of the NBS research program is the investigation of materials with equal or higher charge carrier mobilities than germanium. From a longer-range viewpoint it should be realized that practical solid state electronic devices no longer need be restricted to Si and Ge; the existence of a wide variety of compounds whose properties are virtually unexplored, but which give every indication of being useful, forecasts a latitude in design that was not before possible.

For additional information on semiconductors and solid state electronics see Solid state electronics, *NBS Tech. News Bull.* **35**, 2, 22 (*February 1951*).

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PUBLICATIONS IN OTHER JOURNALS

On smoothing operations and their generating functions. I. J. Schoenberg. Bull. Am. Math. Soc. (531 West One-hundred-sixteenth Street, New York 27, N. Y.) **59,** No. 3, 199 (May 1953).

On the exact evaluation of the variances and covariances of order statistics in samples from the extreme-value distribution. Julius Lieblein. Ann. Math. Statistics (% K. J. Arnold, Michigan State College, East Lansing, Mich.) **24,** 167 (June 1953).

Measurement of treadwear of commercial tires. R. D. Stiehler, G. G. Richey, and J. Mandel. Rubber Age (250 West Fifty-seventh Street, New York 19, N. Y.) **73,** No. 2, 201 (May 1953).

The sieve problem for all-purpose computers. D. H. Lehmer. Math. Tables and Other Aids to Computation (2101 Constitution Avenue NW., Washington 25, D. C.) **7,** No. 41, 6 (January 1953).

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